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14. ABSTRACT
We investigate the use of MIMO to increase the data rate of air to air wireless links without scattered propagation. The conditions for significant improvement over SISO are outlined.

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Aircraft Free-Space MIMO Communications

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Abstract –**We investigate the use of MIMO to increase the data rate of air to air wireless links without scattered propagation. The conditions for significant improvement over SISO are outlined.**

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I. INTRODUCTION

In Airborne Networks, because of the high mobility, a communications link is typically available for only a short period of time. Thus it is desirable to communicate at as high a data rate as possible to complete one's information transfer in the available time. High data rate suggests the use of MIMO communications, multiplexing many messages over the link by using multiple antennas at each end of the link. However, communication between aircraft is usually free of scattered propagation (free space propagation), while MIMO performs best in a highly scattered environment. Nevertheless, MIMO is not necessarily ruled out in such a free space environment, providing the radio frequency is high enough and the antenna arrays are wide enough. We will show how nearly the full data rate advantage characteristic of MIMO links can be achieved in the presence of free space propagation by means of typical examples.

II. F-35 JET AIRPLANES

In this example we assume that two F-35 airplanes are equipped with multi-element slot antenna arrays. As shown in the sketched twelve element array of Figure 1, the slot antenna elements (shown in red) are equally spaced along the front edge of the wings.

The channel matrix is then computed using the locations of the antenna elements on the airplane as shown in Table I.

Figure 1. F-35C Jet Airplane with 12 Element Antenna Array

1

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TABLE I
LOCATION OF ANTENNA ELEMENTS ON THE F-35C (METERS)

Element Number	1	2	3	4	5	6	7	8	9	10	11	12
Longitudinal position	-3.6	-3.18	-2.57	-1.96	-1.36	1.57	1.57	-1.36	-1.96	-2.57	-3.18	-3.6
Lateral position	-6.55	-5.5	-4.45	-3.40	-2.36	-1.31	1.31	2.36	3.40	4.45	5.5	6.55

The distance between two elements, m and n, on the two airplanes, respectively, is

$$r_{mn} = \sqrt{(d - x_n - x_m)^2 + (w - y_n - y_m)^2 + h^2}$$
(1)

where d is the longitudinal separation of the two airplanes, travelling oppositely in the longitudinal direction. The longitudinal and lateral locations of each antenna element on the airplane are x_m and y_m, respectively. The lateral and height displacements of the two airplane paths are w and h, respectively. The transmission coefficient between the two elements is

$$T_{mn} = g_m g_n \frac{\exp(-jkr_{mn})}{r_{mn}},\qquad (2)$$

where g is the voltage gain of the antenna element in the direction of the corresponding element on the other airplane. We make the approximation that the propagation is truly free space, so that $g_m g_n$ is the same for all m and n; i.e., we neglect all blockage by airplane structure, etc. Thus, we construct the normalized Channel Coefficient Matrix, $\mathbf{H}$, as

$$H_{mn} = \frac{\dfrac{\exp(-jkr_{mn})}{r_{mn}}}{\sqrt{\mathcal{E}\left[\left|\dfrac{\exp(-jkr_{mn})}{r_{mn}}\right|^2\right]}},\quad (3)$$

where the expectation, $\mathcal{E}$, is taken over all combinations of m and n. We define the signal to noise ratio, ρ, as that obtained when the total power is radiated from a single element and received by a single

element, averaged over all combinations of m and n. Thus the MIMO channel capacity between the two arrays, assuming only the receiver knows the Channel Coefficient Matrix, is given by [1]:

$$C_{F35} = \log_2\left[\det\left(\mathbf{?}_M + \frac{\rho}{M}\mathbf{HH}^\dagger\right)\right]$$
bits/sec per Hz, (4)

where M is the number of elements in each of the arrays, $\mathbf{?}_M$ is the identity matrix of dimension M, and $\mathbf{H}^\dagger$ is the transpose conjugate of the matrix $\mathbf{H}$. For this study we assume the transmitter uses power control to maintain a constant signal to noise ratio (e.g., $\rho = 10$) as the airplanes approach each other.

For comparison we compute the MIMO capacity of two arrays with the same number of elements in a fully scattered (Rayleigh) environment with the same signal to noise ratio. We average the channel capacity over all instantiations of the scattered propagation. This average channel capacity is called the ergodic Rayleigh capacity, C_R[2]:

$$C_R = M\left\{2\log_2[1 + \rho - F] - \frac{F}{\rho \ln 2}\right\}\quad (5)$$

where $F = 0.25\left(\sqrt{4\rho + 1} - 1\right)^2$.

Another type of channel capacity is that which occurs for a Channel Coefficient Matrix having all equal eigenvalues. This type of channel has the maximum capacity, C_E, for a given signal to noise ratio, ρ, and a given number of elements, M [2]:

$$C_E = M\log_2(1 + \rho).\qquad (6)$$

2

III. DEPENDANCE OF CAPACITY ON DISTANCE AND FREQUENCY

Using the above formulas we compute the channel capacity as a function of distance and frequency for the F-35 airplanes for two arrays with $M = 12$. Figure 2, shows for 10 GHz, the dependence of channel capacity on longitudinal separation for the twelve element array case with 100 m lateral and height separations of the parallel flight paths. Note that the lateral and height separations prevent the airplanes from approaching nearer than 140 meters.
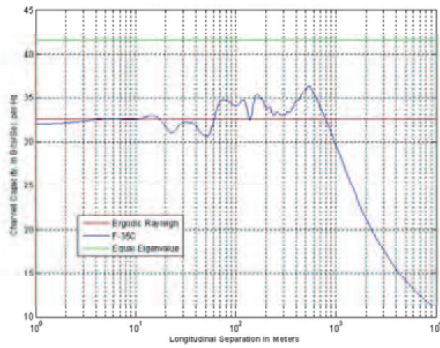

Fig. 2. Free Space MIMO Capacity Between Two F-35CJets with 12 Element Arrays, 10GHz

The channel capacity actually exceeds the ergodic Rayleigh capacity mostly out to a longitudinal separation of 700 m.

The capacity limit for large longitudinal separation is 6.92 bits/sec per Hz, the keyhole[3] single-input-multiple(12)-output (SIMO) capacity.

Modern jets cruise at about 0.25 km/sec. Two jets approaching each other would remain in the 1400 m ergodic Rayleigh MIMO range for about 5.6 seconds at 10 GHz. Of course this oppositely traveling flight pattern is the shortest MIMO duration.

The dependence of channel capacity on longitudinal separation for the case of 120 element arrays on both aircraft was also computed with 100 m lateral and height separations of the flight paths. This dependence is shown in Figure 3 for 10 GHz. The high-capacity MIMO ranges are 0.1 times that for the 12 element array cases, but the MIMO channel capacities are much higher. The MIMO capacity no longer exceeds the ergodic Rayleigh capacity. However, as the radio frequency is increased, the MIMO capacity approaches the ergodic Raleigh capacity even for the 120 element arrays.
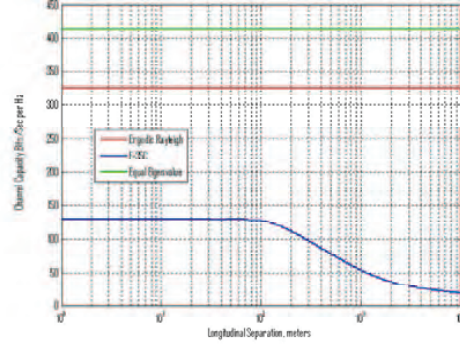

Fig. 3 Free Space MIMO Capacity Between Two F-35C Jets, with 120 Element Arrays, 10GHz

IV. C-5 JET AIRPLANES

Another example of jet airplane is the C-5, with a wing span of 222 feet 9 inches as shown in Figure 4. The C-5 again has a cruising speed of 0.25 km/sec.

Fig. 4. The C-5 Jet Airplane

The positions of the antenna elements for a twelve element array on the wings of the C-5 are given in Table II.

Using the above formulas we compute the channel capacity as a function of distance and frequency for the C-5 airplanes for two arrays. The dependence of channel capacity on longitudinal separation for the twelve element array case with 100 m lateral and height separations of the flight paths is shown in Figure 5 for 1 GHz. Note that

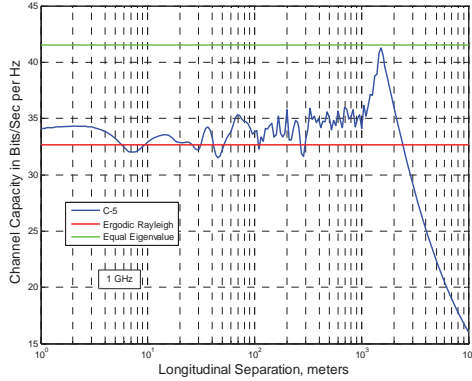| Element Number	1	2	3	4	5	6	7	8	9	10	11	12
Longitudinal position	-9.57	-4.35	-1.02	2.18	5.51	8.76	8.76	5.51	2.18	-1.02	-4.35	-9.57
Lateral position	-33.93	-27.77	-21.61	-15.45	-9.29	-3.13	3.13	9.29	15.45	21.61	27.77	33.93

Fig. 5. Free Space MIMO Capacity Between Two C-5 Jets With 12 Element Arrays

capacity exceeds the ergodic Rayleigh capacity out to a longitudinal separation of 2.5 km for 1 GHz. For 10 GHz that range is 25 km and 250 km for 100 GHz.

For 120 element arrays on the C-5 jets, the high-capacity MIMO ranges are 0.1 times that for the 12 element arrays except the channel capacities are much higher. At 10 GHz, the 120 element arrays provide ergodic Rayleigh channel capacity (325 bits/sec per Hz) out to a longitudinal separation of 2.0 km, corresponding to 8 seconds duration for oppositely traveling C-5 jets at cruising speed.

V. CONCLUSIONS

If one envisions an 1 MHz bandwidth communication link in free space, a transmitted power of 1 Watt is required to provide 10 dB SNR, ρ_{dB} , at 160 km at 1GHz, 16 km at 10 GHz and 1.6 km at 100 GHz:

$$\rho_{dB} = W_{TdBm} + G_{T\,dB} + G_{R\,dB} - B_{dB-Hz}$$
$$- 20\log_{10}(4\pi d/\lambda) - F_{dB} + 174_{dBm/Hz} \quad . \quad (7)$$

where d is the distance in meters, λ is the free space wavelength in meters, $G_{TdB} = G_{RdB}$ are the transmit and receive array element gains, respectively, which are about 3 dB, W_{TdBm} is the total transmitted power in decibels above a milliwatt, B_{dB-Hz} is the bandwidth in dB above 1 Hz, F_{dB} is the receiver noise figure in dB, which we approximate by 3 dB, and 174 is the room temperature thermal noise in dBm/Hz.

At cruising speed, for the oppositely traveling aircraft, at 32.5 bits/sec per Hz, an 182 Mbit message could be transmitted in 5.6 seconds (12 element F-35 jet at 10 GHz). For 325 bits/sec per Hz, a 2.6 Gbit message could be transmitted in 8 seconds (120 element C-5 jet at 10 GHz). At sea level, 100 GHz atmospheric attenuation for dry air is 0.3 dB/km and moist air is 5 dB/km. At aircraft cruising altitudes, we can neglect atmospheric attenuation for the short distances involved. For comparison, a standard 12 cm single sided DVD contains about 38 Gbits of data.

Tactics may allow the communicating aircraft to fly in the same longitudinal direction which, with equalized flight speed, would allow much longer communications while remaining close enough for the large data rates allowed by MIMO communication.

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